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# Additive manufacturing of mirror components for space

Carolyn Atkins et al.  
UK Astronomy Technology Centre

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# Context

This presentation is linked to the poster presented yesterday:  
**Additively manufactured mirrors for CubeSats**

The results described in this presentation highlight the optical performance expectation for the CubeSat substrates.



UK Research and Innovation



Additively Manufactured Mirrors for CubeSats


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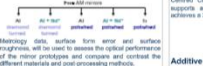
### 1. Project Overview

This project aims to design, build and evaluate 8 additively manufactured (AM) 10° steering mirrors for integration with a 3U CubeSat telescope for Earth observation (EO) as observational capabilities. The use of AM fabrication allows to address the Mirror challenge of high quality optical performance in combination with light-weight structures required by launch-weight restrictions.

Ensuring the benefits of AM fabrication, 3 optical mirrors have been manufactured: 2 aluminum (Al), 2 fiber-reinforced carbon aluminum (Al + HF) and 1 3U aluminum (3U).



On-axis mirror concept



Identifying data, surface, form error and surface roughness will be used to assess the optical performance of the mirror prototype and compare and contrast the different materials and processing methods.

**Success Criteria**

- The AM Al mirrors, one polished and one diamond turned, with a reflecting surface that meets enhanced wave-length requirements.
- The AM Al + HF mirrors, one polished and one diamond turned, with a reflecting surface that meets visible wave-length requirements.
- A novel light-weight mirror design, incorporating the structural benefits of AM.


### 3. Mirror Design and Fabrication

#### Mechanical Design Characteristics

- The mirror design is based on a flat disk such as per consideration and light-weighting.
- The mirror design is identical in the different prototypes ensuring that the resultant optical surfaces can be compared.
- The design can easily be integrated into a 3U CubeSat.

#### Lattice Choice

To achieve light-weighting, a geometric lattice was used, oriented for a vertical tube. The design follows a Body-Centered Cubic (BCC) unit cell such that no internal supports are required leaving the tube. The design achieves a 30% weight reduction.




Body-Centered Cubic (BCC) unit cell

#### Additive Manufacture Design

Design modifications are normally required in order to produce a printable design. Further, suitable post-processing features are typically required for additively-manufactured parts. The considerations for the project include:

- Additional material around the outer circumference prevents under surface finish.
- Radius to allow easier powder out.
- Smooth edges to be used during machining.
- Internal curvature ensures priority in the vertical build direction.
- Reduction of integrated mounting features.



Half size of the printed structure showing the lattice, mounting base and internal curvature.

#### Machined Design

The mirror design incorporates a sandwich structure with light-weighting as well as integrated mounting features and flanges.




Image of machined mirrors


An AM prototype, representative of the mirror substrate and lattice structure, was manufactured and post-processed.

Image credit: NPL

### 4. Design Optimisation

Topology optimisation was used to explore further potential light-weighting designs. The core features of the reinforcement sandwich mirror were kept the same and the mirror's internal structure was optimised for stiffness.


#### Optimisation with Side Walls



The optimisation produced the following internal support structures:

20% volume reduction (A)    80% volume reduction (B)    75% volume reduction (C)

#### Optimisation without Side Walls



Resulting in the following support structures:

20% volume reduction (A)    80% volume reduction (B)    75% volume reduction (C)

### 5. Future Work

The post-processing of the mirror substrates will be completed. Optical metrology and subsequent analysis will be undertaken by the UCL/STFC.

The mirrors will be measured for:

- Form error and radius of curvature
- Surface roughness
- Print-through effects

An optimised design will be selected, based on a compromise between light-weighting and predicted optical performance.

The results will be presented at the SPIE Optics + Photonics conference in San Diego, August 2019.

### References



[1] CubeSat Camera: A Low Cost Imaging System for CubeSat Platforms, Willem Brouwer et al. *CubeSat 8th International Conference Workshop*, 2015.

[2] The use of additively-manufactured optical structures for earth observation satellite imaging: introduction for Additive Manufacturing, Pearson et al. *IC 2019*, 2019.

### Acknowledgements

The research was funded by the UK Space Agency National Space Technology Programme and has been given 100% RCUK funding.

Authors are grateful to the Department for Business, Energy & Industrial Strategy and the Department for International Trade for their support for the National Measurement System Programme which funded part of this work.

# Outline

1. Motivation and approach
2. AM mirror example #1 – good surface roughness can be achieved
3. AM mirror example #2 – lightweighting comparison
4. Conclusion

# Motivation: why additive manufacturing?

To utilise the design freedom of AM to create bespoke hardware that is more tailored to function than tailored to manufacturability.

*Question: Why create mirrors via AM?*

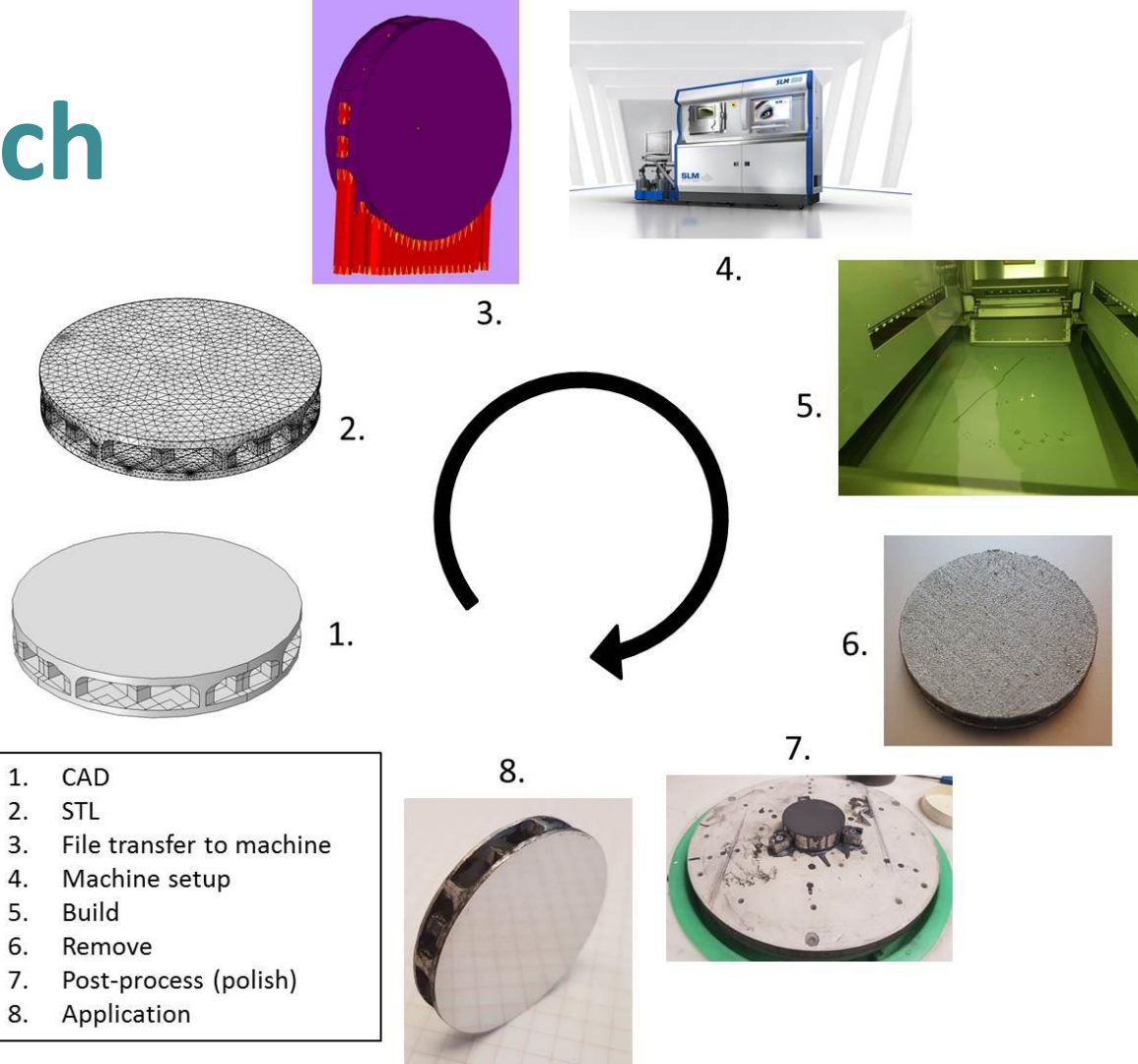
*To develop mirrors more suited to their environmental constraints:*

- Optimised light-weighting
- Integrated mounting or functionality.

*Question: Why create AM mirrors for space?*

- Reduce weight
- Optimise volume use
- Demise-ability

# Approach

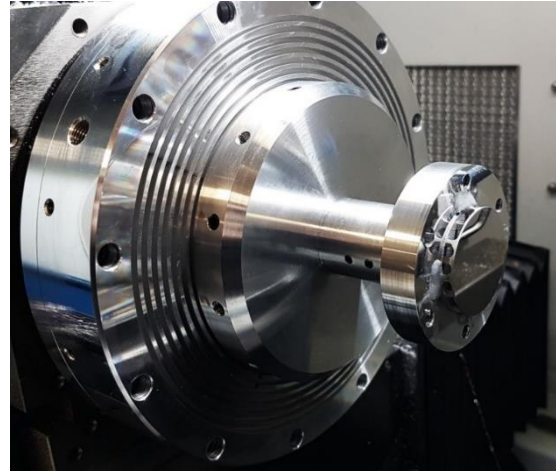


- |    |                          |
|----|--------------------------|
| 1. | CAD                      |
| 2. | STL                      |
| 3. | File transfer to machine |
| 4. | Machine setup            |
| 5. | Build                    |
| 6. | Remove                   |
| 7. | Post-process (polish)    |
| 8. | Application              |

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# AM Example #1: the aluminium mirror



Dimensions: 40mm in diameter, 6mm in height, **optically flat**

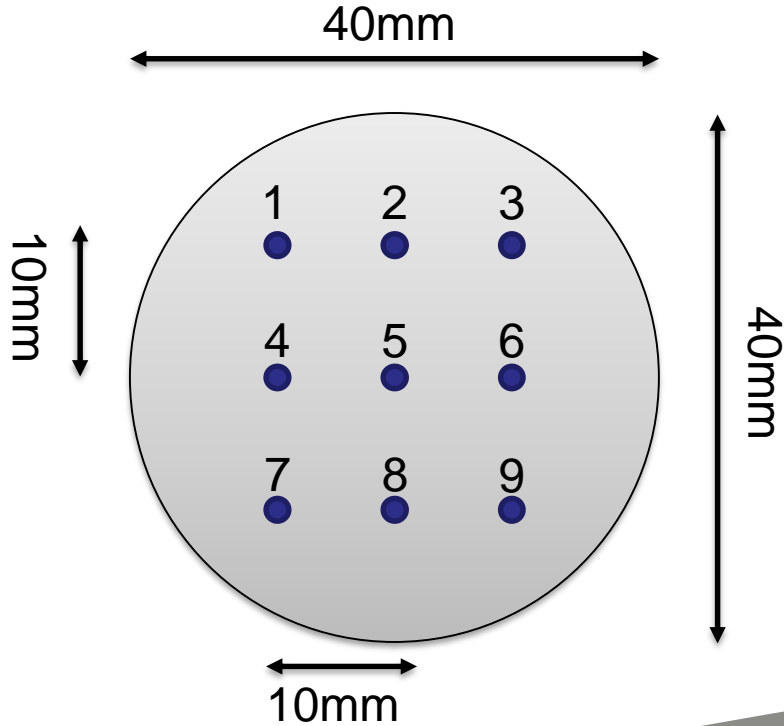
Material: aluminium (AlSi<sub>10</sub>Mg)

Lightweight percentage: ~44% mass remaining (ratio = 9g/20.36g)

Single Point Diamond Turning: RAL Space PDF

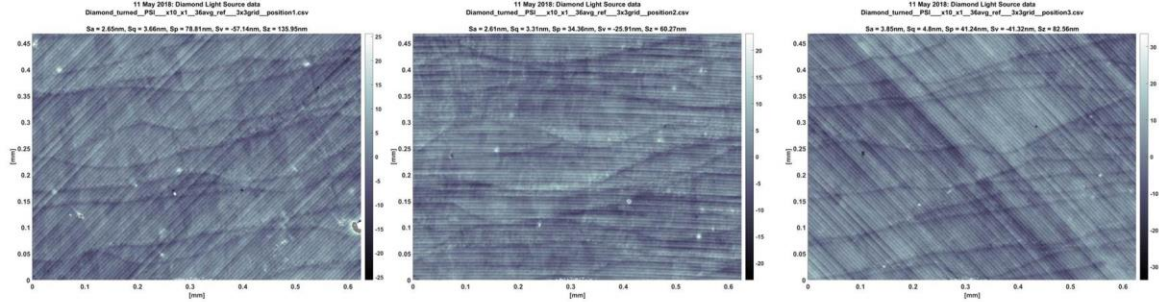


# Diamond-turned AM mirror

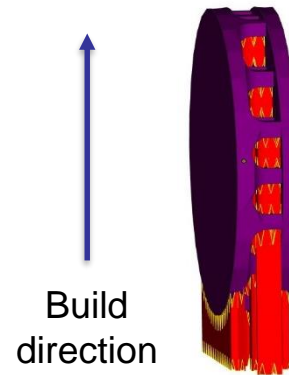
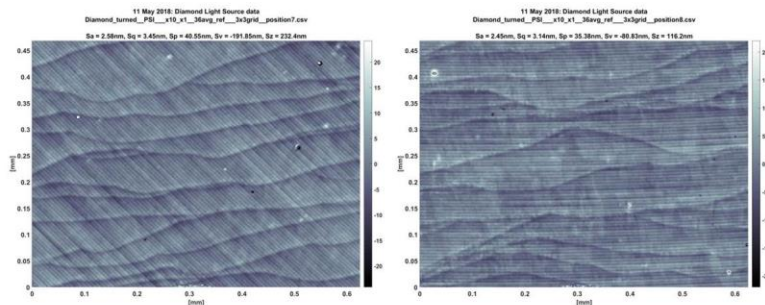
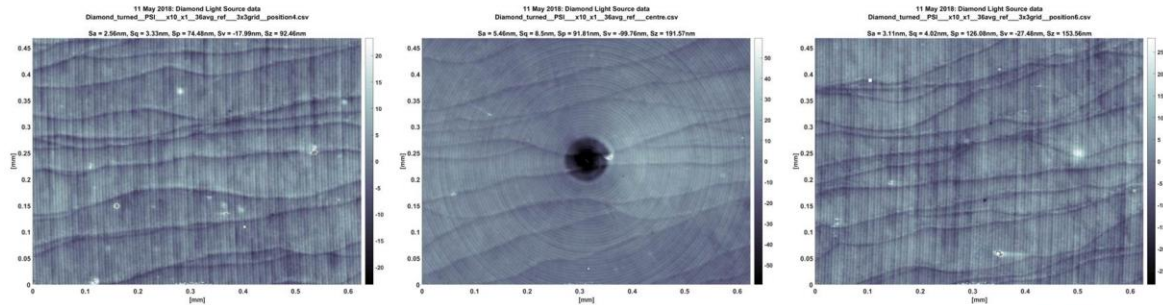


## Surface roughness:

- Facility: Diamond Light Source
- Instrument: Bruker Contour GT-X stitching microinterferometer
- 3 magnifications evaluated: 5x, 10x and 50x



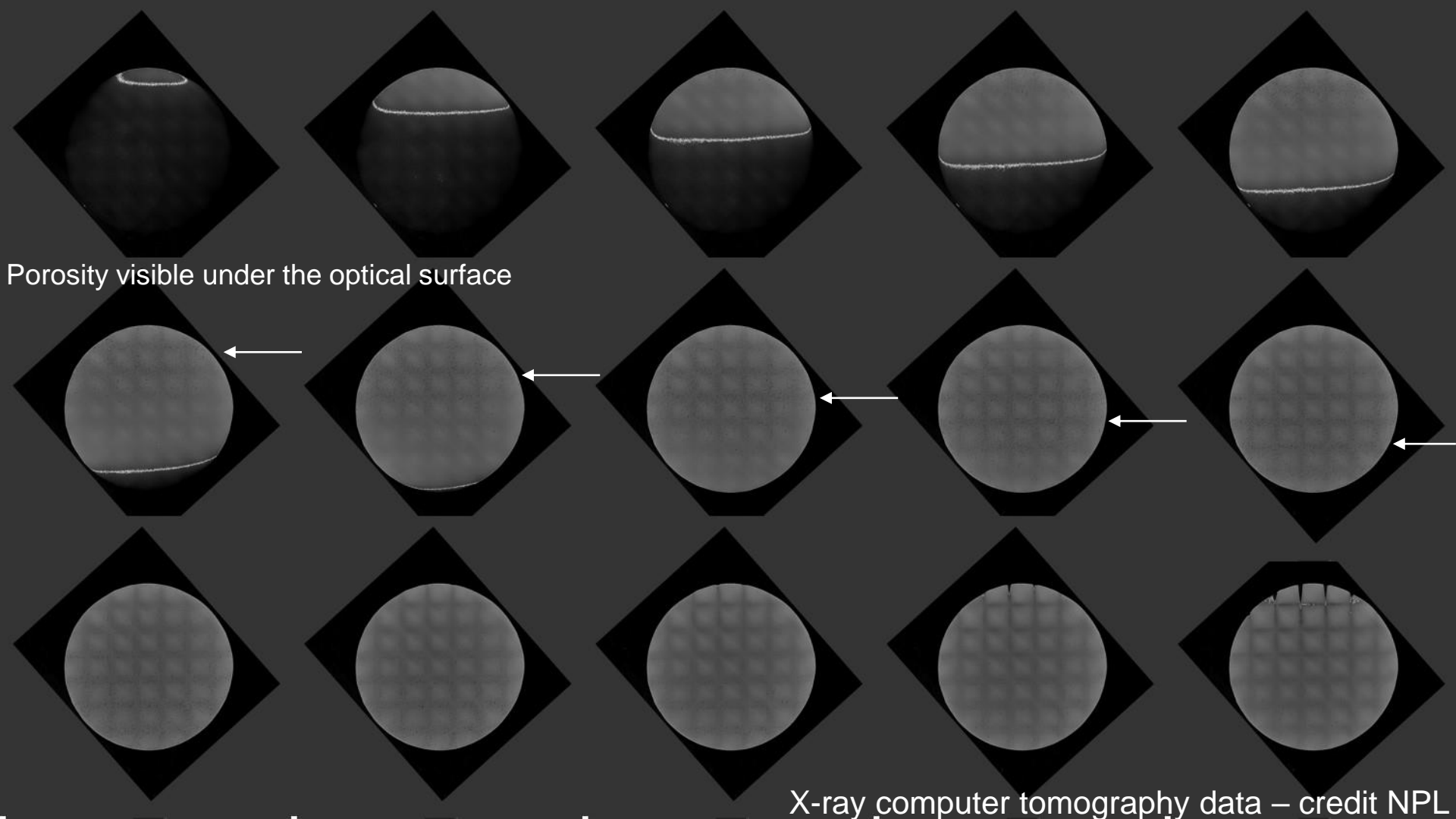
10x magnification



# Surface roughness data

Surface roughness measurements						
3x3 Grid	5x magnification		10x magnification		50x magnification	
	RMS[nm]	PV[nm]	RMS[nm]	PV[nm]	RMS[nm]	PV[nm]
Ave.	<b>3.28</b>	<b>91.41</b>	<b>3.66</b>	<b>117.95</b>	<b>3.84</b>	<b>40.56</b>
Max.	5.00	105.82	4.80	232.40	4.92	66.25
Min.	2.55	67.04	3.14	60.27	3.10	24.08

*... these are good values for aluminium, where's the porosity?*

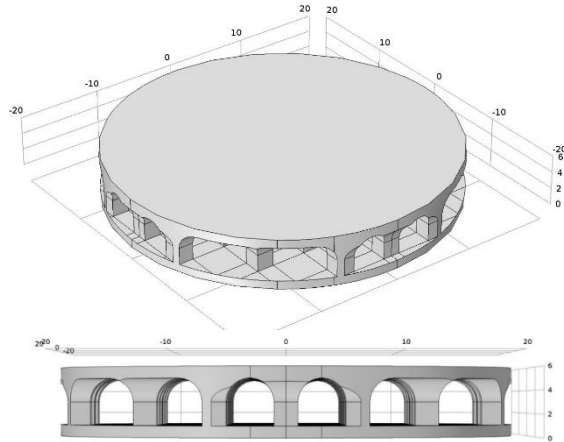


# Outline

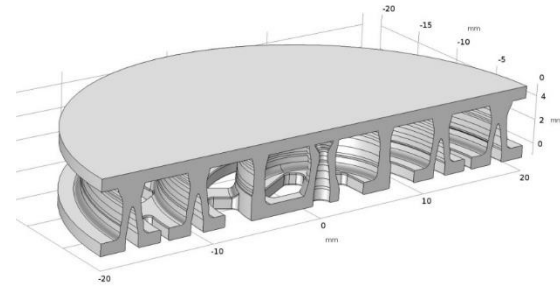
1. Motivation
2. AM mirror example #1 – good surface roughness can be achieved
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# Design optimisation

40mm diameter, 6mm in height,  
top and bottom substrate  
thickness 1mm.



40mm diameter, 5mm in height,  
top and bottom substrate  
thickness 0.5mm.



Design output from topology optimisation  
– light-weighting designed to compensate  
for polishing pressure

Core research discussed in: *Atkins, C. et al., "Additive manufactured x-ray optics for astronomy", Proc. SPIE 10399, 103991G, 2017.*

# Design comparison

Material: AM aluminium (AlSi<sub>10</sub>Mg)  
Coating: nickel phosphorous (NiP)  
Diameter: 40mm

Ensures a pore free surface to polish

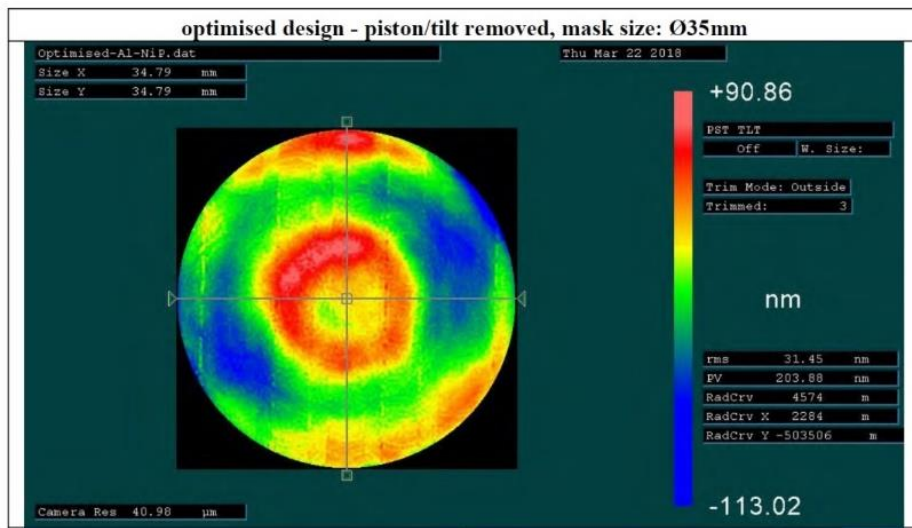
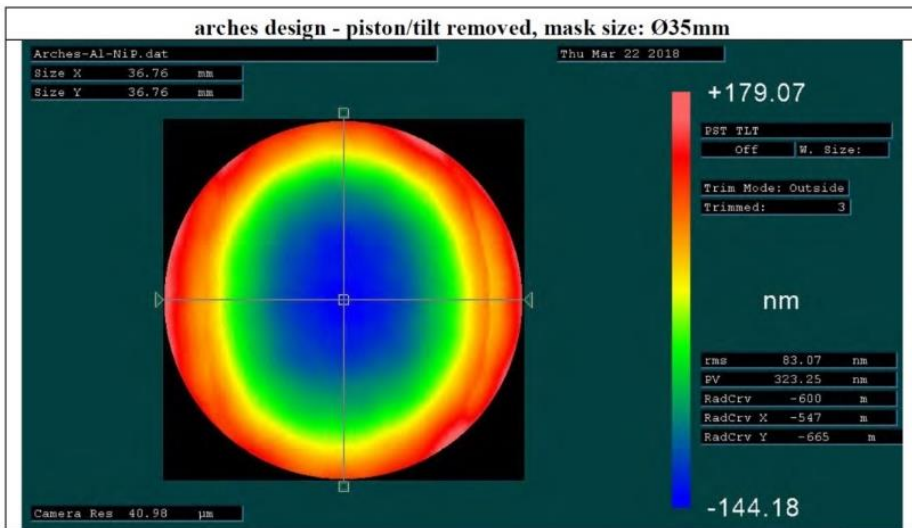
Substrate thickness: 1mm  
Weight: 14.3g



Substrate thickness: 0.5mm  
Weight: 11.7g



# Form error after polishing

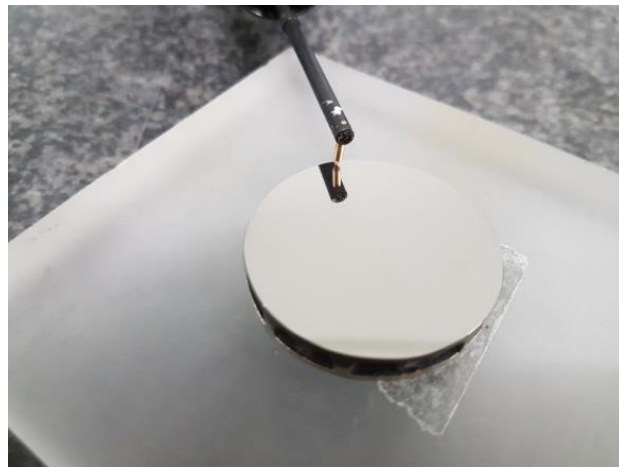
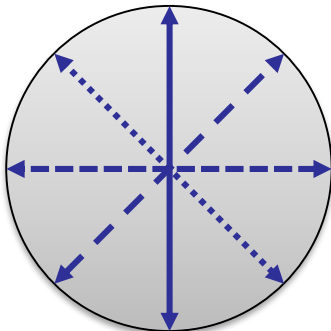
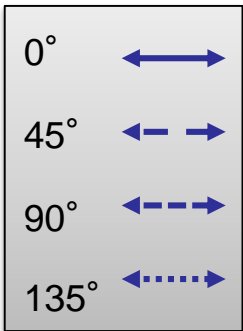


Surface form error:

- Facility: European Synchrotron Radiation Facility
- Instrument: ZYGO GPI – XPZ,  $\lambda = 632.8\text{nm}$



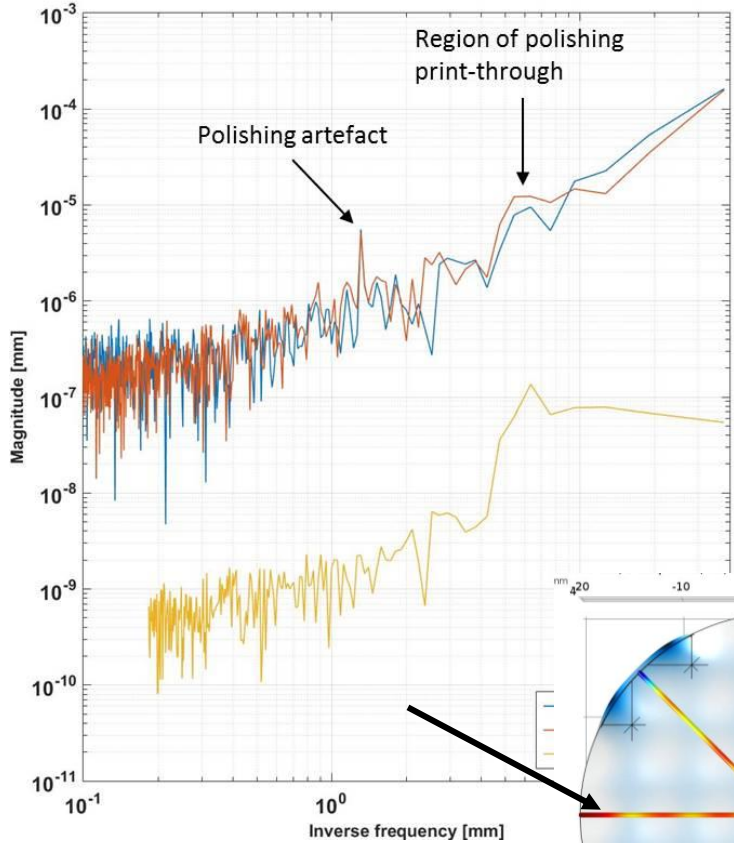
# Does the light-weighting print-through?



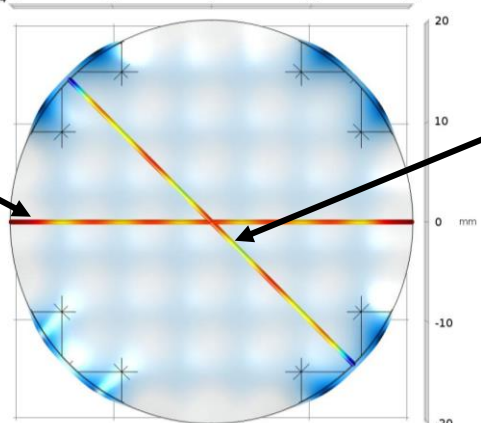
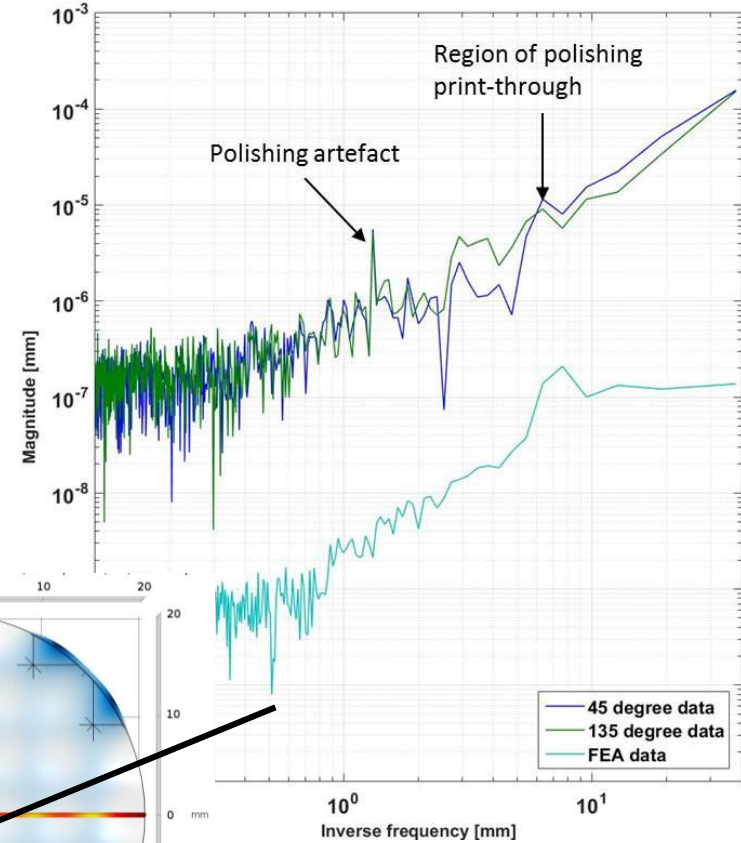
Profilometry data:

- Facility: Glyndwr Innovations
- Instrument: Taylor Hobson Form Talysurf Intra.

Measurement data from AISi10Mg + NiP in the 0 and 90 degree orientation



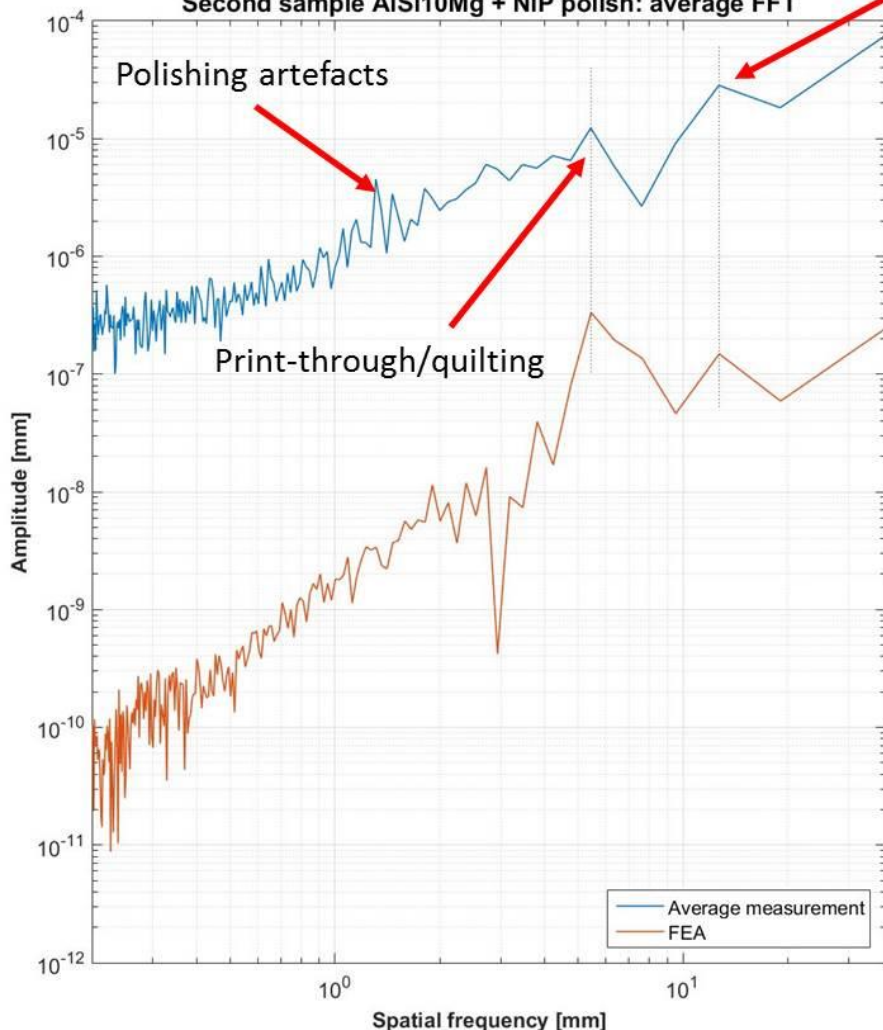
Measurement data from AISi10Mg + NiP in the 45 and 135 degree orientation



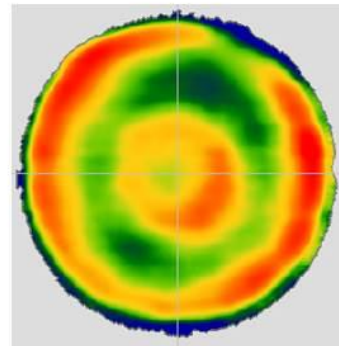
— 45 degree data  
— 135 degree data  
— FEA data

16-Oct-2017

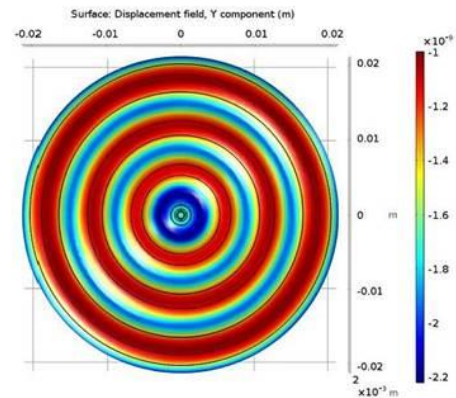
Second sample AISi10Mg + NiP polish: average FFT



Form seen in interferometer



FEA print-through map



# Optical form

Form error	Non-optimised	Optimised
PV [nm]	323.25	203.88
RMS [nm]	83.07	31.45
Weight [g]	14.3	11.7
<b>Roughness [x5 magnification]</b>		
RMS [nm]	3.37	6.04
<b>Print-through of light-weighting [FFT]</b>		
Amplitude [nm]	<10nm	~10nm

## Take away

1. Reasonable form error can be achieved using AM substrates.
2. Computer optimisation is worth the time investment.

These results demonstrate a first effort in this research area

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# Predicted impact

- Access to missions:
  - Use of AM mirrors could be applied where ever optical elements are required within a system.
- Mission enablement:
  - Allows more innovative, weight saving designs.
  - Cost – AM mirrors are no more expensive than traditional lightweight mirrors, perhaps less so.
  - Less weight per aperture area.
- Science enablement:
  - Larger collection area for a given mass restriction.
- Commercial:
  - Many of the big companies already have the required AM capability to build these parts.

# Acknowledgements

- Part of this research was funded by the **UK Space Agency** National Space Technology Programme via a Pathfinder grant – NSTP3 PF 007.
- This project has received funding from the **European Union's** Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 665593 awarded to the Science and Technology Facilities Council.
- C. Atkins acknowledges the **STFC Rutherford International Fellowship** for the freedom to do this research.
- Authors are grateful to the Department for Business, Energy & Industrial Strategy and their support of the National Measurement System Programme which funded part of this work.
- **Glyndwr Innovations** for the use of metrology equipment



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